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CLASSICAL AND HOLOGRAPHIC GRATINGS.
EFFICIENCY PROBLEMS AND THEIR BEARING ON INSTRUMENTAL SPECTROSCOPY

J. Cordelle, J.P. Laude, R. Petit, and G. Pieuchard

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15. Supplementary Notes

16. Abstract

Previous results concerning metal gratings with a triangular profile are reviewed. We present the first experimental results on the efficiency of holographic gratings and indicate their significance in instrumental spectroscopy: Using classical gratings in Littrow mounting and nonpolarized light, we numerically construct a chart which permits the determination of the appropriate grating parameters for a given spectroscopic application.

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J. Cordelle, J.P. Laude, R. Petit, and G. Pieuchard
Research Laboratory of the Jobin-Yvon Company

Introduction   /149*

Recent articles have drawn attention to a new type of diffraction grating: holographic gratings. It has been shown that, for concave holographic gratings, there are important stigmatic effects which do not exist for classical concave gratings. The absence of ghosts and diffused light makes them especially suitable to spectroscopic uses and, in specific conditions, one can obtain spectra that are practically free of any aberration or stray light. While it is important to be concerned with the quality of the image, it is also necessary to consider its brightness. This article will treat the efficiency of the gratings, that is to say, for a given experimental setup and a given order, we will examine the ratio of the incident flux to the diffracted flux as a function of the wavelength; we then draw efficiency curves which show how the diffracted flux is distributed in the spectrum for a given order.

There are still many unsolved problems in the area of grating efficiency. We review the investigations of metal gratings with triangular profile, we submit the first experimental data on the efficiency of holographic gratings, and we indicate their significance in instrumental spectroscopy.

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I.   Grating Efficiency

I.1.   Metal Gratings with Triangular Profile

The phenomenon of diffraction by a grating is a consequence of Helmholtz' equation and the conditions at the limit determined by the profile of the rulings. In general, the efficiency will be different depending on whether it is the electric field E or the magnetic field H that is parallel to the rulings; the efficiency curves are also different depending on the polarization. For nonpolarized light, we take the efficiency to be the average of the efficiencies observed in the cases $E_\parallel$ and $H_\parallel$, where the fields E or H, respectively, are parallel to the rulings.

The efficiency of plane metal gratings with triangular profile is now well known. The theoretical results have been confirmed by experiments which, in the visible region, require a precise determination of the profiles with the help of an electron microscope (Figs. 1, 2, and 3).

For practical purposes, the following should be borne in mind:

-- When the ratio λ/d is less than 0.3 (which is always true when the blaze angles are less than 8°), the efficiency curves for $E_\parallel$ and $H_\parallel$ overlap. For an order k, the maximum efficiency occurs at the wavelength

$$\lambda_\it{b} = \frac{2\,d \sin \alpha}{k}.$$
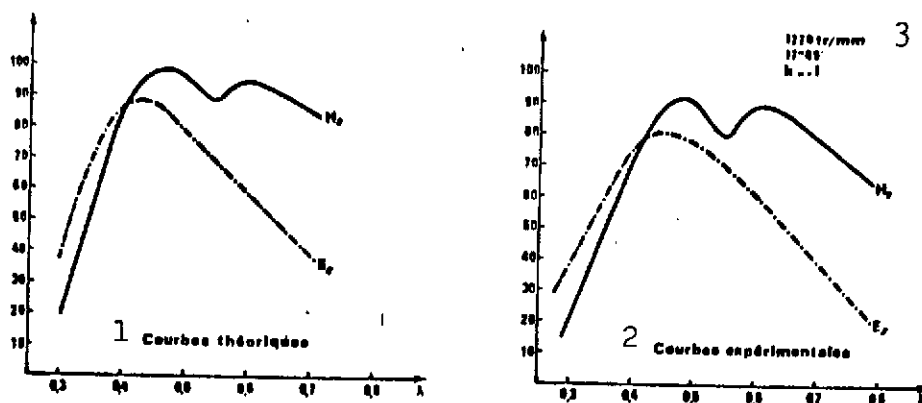
Fig. 1. Grating with 1220 rulings/mm. $\alpha = 17°45'$
Efficiency curves $E_{||}$ and $H_{||}$ for an order $k = -1$

in a Littrow setup $\lambda_{K_{||}} = 0.45\,\mu$; $\lambda_{H_{||}} = 0.47\,\mu$; $\lambda_{B} = 0.5\,\mu$.

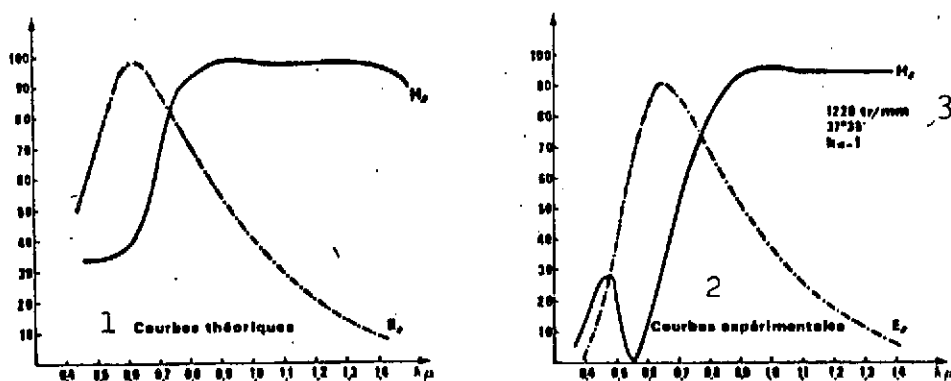Key: 1. Theoretical curves
     2. Experimental curves
     3. Rulings/mm

Fig. 2. Grating with 1220 rulings/mm. $\alpha = 37°35'$.
Efficiency curves $E_{||}$ and $H_{||}$ for an order $k = -1$

in a Littrow setup $\lambda_{K_{||}} = 0.62\,\mu$; $\lambda_{H_{||}} = 0.9\,\mu$; $\lambda_{B} = 1\,\mu$.

Key: 1. Theoretical curves
     2. Experimental curves
     3. Rulings/mm

Figs. 1 and 2. Comparison of the experimental and theoretical efficiency curves.

Experimentally, the efficiency is zero (black line in the spectrum) in the case $H_{||}$ when $\lambda = 0.55$ µm; this abnormality does not appear on the theoretical curve. The reason for this is very simple: the points correspond to the wavelengths 0.5 µm - 0.6 µm...

predicted by an approximation (scalar theory) derived from the Huygens-Fresnel principle, whatever the polarization of the incident field. λ_B is known as the "blaze wavelength."

-- As the ratio λ/d increases, the $E_{||}$ and $H_{||}$ curves become quite different and more so when the blaze angle is greater. Each one reaches a maximum corresponding to different wavelengths $\lambda_{E_{||}}$ and $\lambda_{H_{||}}$. Experiments and computations seem to indicate that the average efficiency decreases when λ/d (or α) increases and $\lambda_{E_{||}} < \lambda_{H_{||}} < \lambda_B$.

These polarization properties can be taken advantage of in certain setups using a laser. A grating with 152 rulings/mm with a blaze angle of 37° can be used as a mirror for the cavity of a CO_2 laser (emitting at approximately 10 µm), provided that the rulings are parallel to the magnetic field (see Fig. 2). However, in most spectrometric problems, polarization effects are undesirable. Spectral analysis of the sources is generally for ordinary light (not polarized) and in this case the efficiency does not always reach the high values erroneously predicted by the scalar theory.

I.2. Holographic Gratings. First Experimental Data on the Efficiency

The investigation of efficiency problems has just begun. For each manufactured grating, we have limited ourselves to draw the
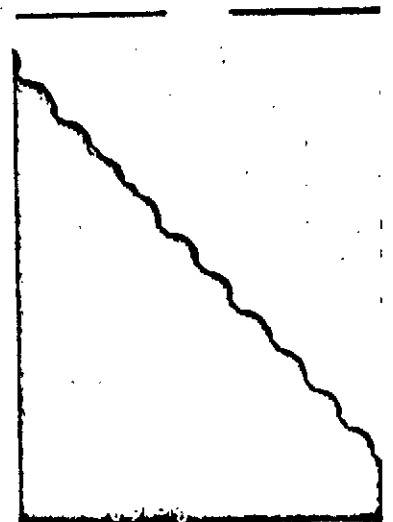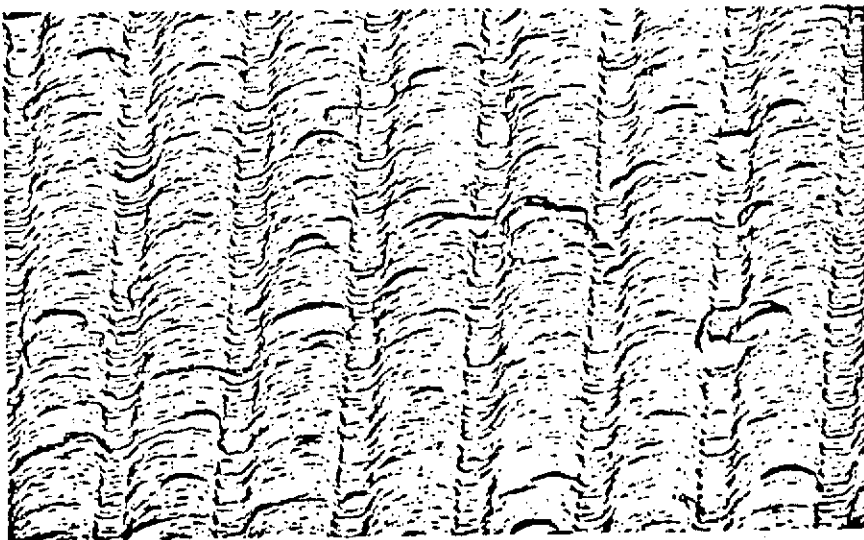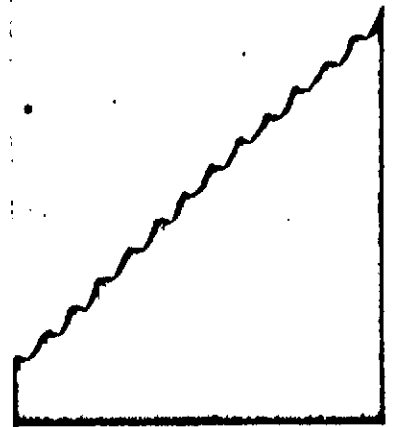
Fig. 3. Micrographs of a classical grating (left) and a holographic grating (right) with 1200 rulings/mm (taken by the laboratory for optics and physical crystallography of the Faculté des Sciences of Marseille).

curves for the two cases $E_{||}$ and $H_{||}$, and we examine the profile under the electron microscope. Polarization effects as well as abnormalities (black lines in the spectrum) are observed, but we are not yet in a position to determine or analyze the energetic

properties of the holographic gratings produced. The curves are different from one grating to another, and we can not as yet control the parameters which affect their overall shape, nor can we obtain acceptable replications of the observed data (see Fig. 4).

A theoretical investigation is now in progress and it should be greatly facilitated by the method recently suggested by J. Pavageau.
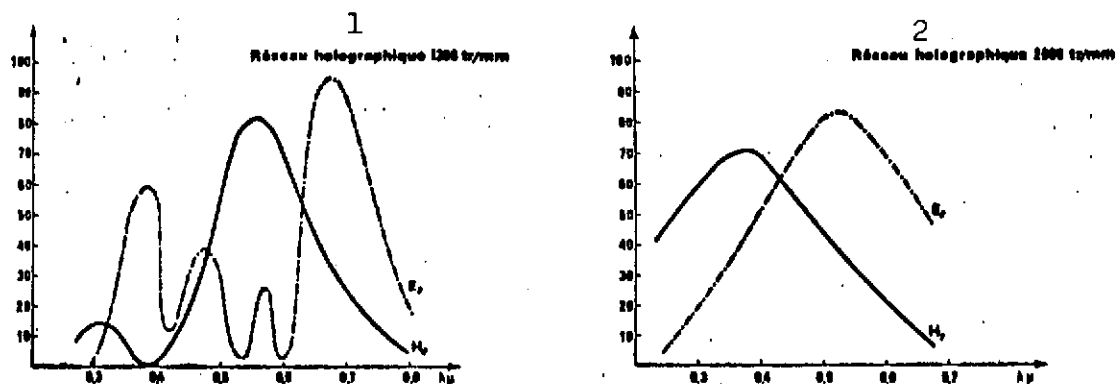

Fig. 4. Holographic gratings. Experimental efficiency curves.

Key: 1. Holographic grating, 1300 rulings/mm
     2. Holographic grating, 2000 rulings/mm

I.3. Conclusion

While the theoretical efficiency of metal gratings with triangular profile is now well known, this is not the case for holographic gratings whose profile is far from being triangular (see Fig. 3). Experimental investigations in the visible region show, however, that the maximum efficiencies of holographic gratings are often the same as those of classical gratings with

high resolving power. The resulting profile depends on many factors: thickness of the resin layer, length of exposure, development procedures. The efficiency which depends on the profile is, in fact, dependent on all these factors, and also on the nature of the metal or dielectric deposit over the photosensitive resin. A systematic investigation is now in progress.

The results we have just reviewed bring up the following question:

How should one choose a grating suitable to a given spectroscopic problem? In general, the more dispersion, the more polarization effects, and the more the average efficiency decreases. Does the gain in resolution compensate the loss of brightness? This is the problem that we shall try to solve; we consider only classical gratings mounted in a "Littrow setup" where the spectrometer is to analyze the spectrum of a nonpolarized light source.

II. Significance for Instrumental Spectroscopy

II.1. General Considerations (See Fig. 5)

Consider a spectrometer mounted in the Littrow setup with a grating of width M, height H, grating constant d and blaze angle α; we wish to perform a spectral analysis, in the order k, of a line with an average wavelength λ_0. The entry and exit slit have the same dimensions: angular width ω, angular height β. Let ε be the angular width of the diffraction figure given by the grating and
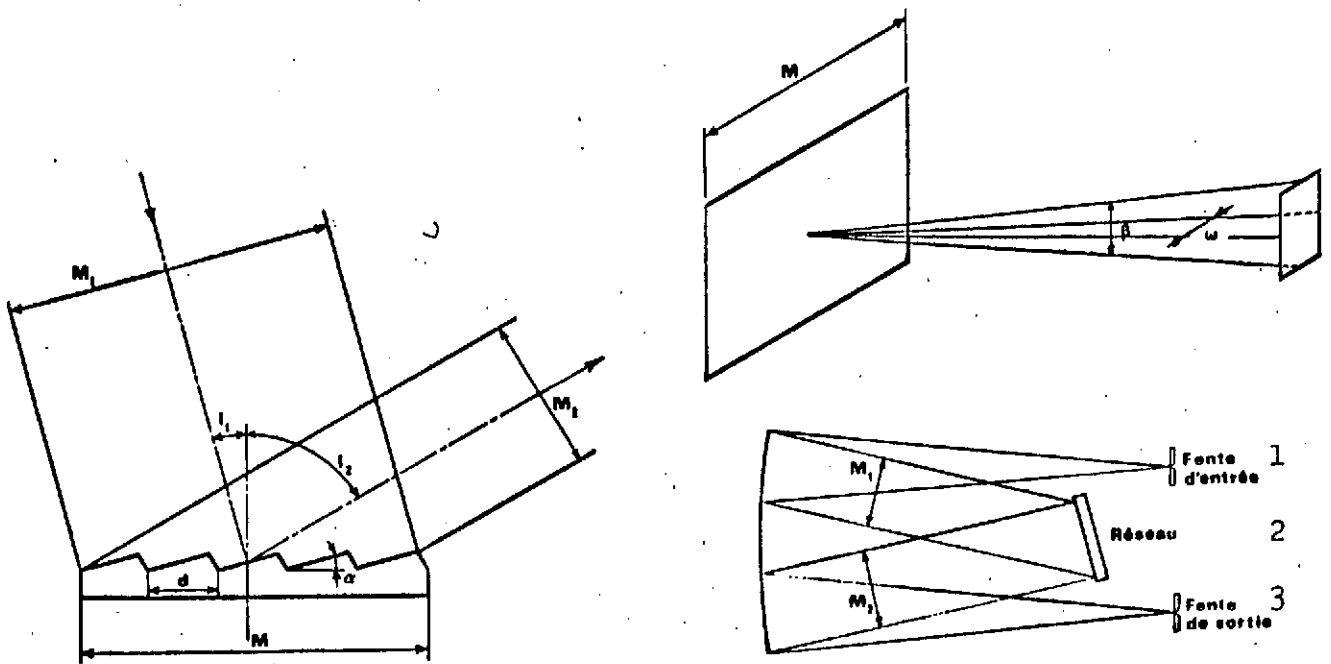
$$R_0 = \frac{k}{d} M$$

Fig. 5.   Diffraction diagram for a grating with constant d, blaze angle α: sin i_1 + sin i_2 = k, λ/d in a Littrow setup i_1 = i_2 = θ 2sinθ = kλ/d.

Diagram of a spectrometer with a grating.

Key: 1.   Entry
     2.   Grating
     3.   Exit

be the intrinsic resolvance of the grating.

Finally, it is assumed that the transmission factor of the spectrometer is practically identical to the grating efficiency E which is a function of λ/d, α and k.

It is known that if the angular width ω of the slits is much greater than the angular width ε of the diffraction figure (normal operating conditions of a spectrometer, triangular function), the resolution R of the spectrometer and its luminosity L are, respectively:

$$R = M \frac{k}{d} \frac{s}{\omega}, \quad \text{or} \quad R = R_0 \frac{\varepsilon}{\omega}$$

and

$$L = EH\beta \frac{\lambda_0}{8} \omega.$$

Therefore:

$$LR = EH\beta k \frac{\lambda_0}{d} M = EHM\beta\lambda_0 R_0 = L_0 R_0.$$

where L_0 is the luminosity of a spectrometer operating with a resolution R_0.

In order to maximize the product LR, one must maximize the expression:

$$k \frac{\lambda_0}{d} E\left(k, \frac{\lambda}{d}, \alpha\right).$$

Using the data from numerous numerical calculations carried out by a computer, we have drawn the following curves for each grating produced:

-- the efficiency curves as a function of λ/d for given α and k,

-- the efficiency curves as a function of α for given λ/d and k.

On the basis of the latter, we have determined the values $\alpha_M(k, \lambda/d)$ of the blaze angles at which the efficiencies reach their maxima $E_M(k, \lambda/d)$.

We thought it might be interesting to summarize this tedious process by showing on the same graph the various curves C_k which, for given k, show the variations of

$$y_k = k \frac{\lambda}{d} E_M\left(\frac{\lambda}{d}, k\right).$$

as a function of $x = \lambda/d$. Two curves for $k = 1$ and $k = 2$ are shown in Fig. 6. It should be noted that the abscissas of the various points of a curve C_k are less than $2/k$ (since in a Littrow mounting: $k, \lambda/d < 2$) and that their ordinates are always less than $k, \lambda/d$, since E is always less than 1. It should also be noted that in this particular representation, the efficiency of the grating corresponding to the point $M_k(\lambda/d, y_k)$ can be found very easily: simple geometry shows that it is the ordinate of the point of intersection of the straight line OM_k and the straight line Oy whose equation is $x = 2/k$. In a given order, the straight lines from the origin are therefore curves of iso-efficiency graded from 0 to 100.

II.2. An Illustration of the Use of the Charts (Fig. 6)

Suppose we wish to build a spectrometer of range U in order to analyze a radiation λ_0 with resolution R. If the height of the grating is H and the angular height of the slits is β, how shall we select the appropriate grating?

In other words, when going through a manufacturer's catalogue, how do we choose the grating constant? What should be the width M, the blaze angle α of the grating, and in what order should it be working? The data give us a definite value of R_0 because:
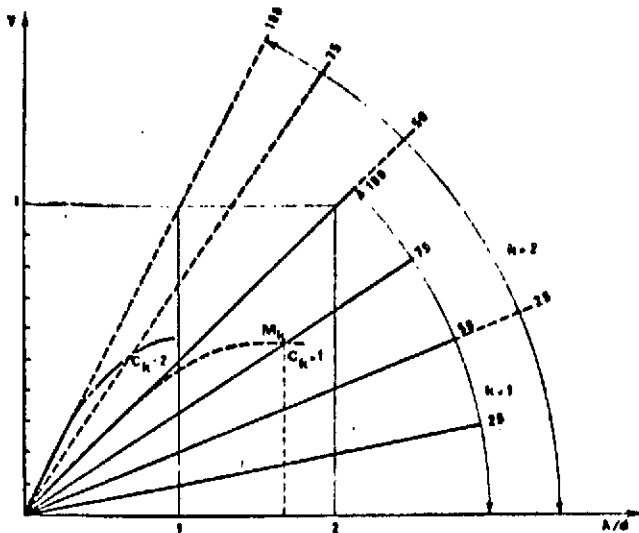
$$M_2 \beta = \lambda_0$$

Fig. 6. Chart used to determine the parameters of a grating for a given spectroscopic application.

$$M_2\,\omega = \frac{U}{H\beta}$$

(the range in the image space is $U = M_2 H \omega \beta$)

$$\frac{R}{R_0} = \frac{\varepsilon}{\omega} R_0 = R \frac{\lambda_0\, H\beta}{U},$$

and R_0 is known.

A priori, any grating can be used: the only condition is that it should work in an order k such that $k(\lambda_0/d) < 2$. The choice can be made on the basis of the charts: One makes a list of the various ratios λ_0/d compatible with the grating constants proposed by the manufacturer (d = 1800, 1200, 600, ... mm^{-1}). For each value of λ_0/d there are points M_k of ordinate y (provided, however, that $k(\lambda_0/d) < 2$). The point M_k with the greatest ordinate indicates the grating constant d of the appropriate grating and the order k in which it should be operating. The optimal blaze angle can then be determined by referring to the graphs showing the efficiency as a function of α, for given λ/d and k. The width M is also determined: M = R(d/k).

There may be, of course, other considerations, such as the quality of the ruling, the amount of stray light, etc., which depend on the grating constant, the order and the blaze angle. The price may be a decisive factor! The influence of the latter has been neglected since we have not limited, a priori, the width of the grating.

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